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JRC reference data from experiments of on-board hydrogen tanks fast filling

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ABSTRACT

At the JRC-IET, on-board hydrogen tanks have been subjected to filling–emptying cycles to investigate their long-term mechanical and thermal behaviour and their safety performance. The local temperature history inside the tanks has been measured and compared with the temperatures outside and at the tank metallic bosses, which is the measurement location identified by some standards. The outcome of these activities is a set of experimental data which will be made publicly available as reference for safety studies and validation of computational fluid dynamics.

Introduction

Hydrogen technologies have to comply with a set of safety standards and regulations. Regulations, codes and standards (RCS) concerning the performance assessment and safety testing of hydrogen components for transport, stationary and mobile applications have been developed and reviewed in the last years. Regarding on-board hydrogen tanks one of the first standardization works has been performed by SAE International in 2008: the Technical Information Report J2579 on vehicular hydrogen systems is a performance-based standard aimed at guaranteeing safety operation during the whole life of hydrogen pressurized components [1]. A revision of the SAE J2579 standard has been published in March 2013. The International Standard Organisation has as well produced standards for land vehicle fuel tanks for liquid and gaseous hydrogen storage [2,3].

Parallel to standardization activities, and often building upon them, legally binding regulations are being developed at national and international levels. The Commission Regulation (EU) No 406/2010 of 26 April 2010 [4], implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles [5] contains the implementing measures such as the individual tests of the hydrogen vehicle's components required for the type approval. Typical tests for high pressure tanks are: burst test, bonfire test (resistance to fire), chemical exposure test, ambient temperature and extreme temperature pressure cycle tests, accelerated stress rupture test, impact damage

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test, leakage test, hydrogen gas cycling test. The United Nations Economic Commission for Europe (UN-ECE) Global Technical Regulation for Hydrogen Fuelled Vehicles [6], approved in June 2013, contains compliance tests for fuel system integrity and test procedures for compressed hydrogen storage and for electrical safety.

There is a need of harmonization regarding technical implementation of test requirements and procedures as proposed by these regulations codes and standards. At the International Hydrogen Fuel and Pressure Vessel Forum 2010 technical experts presented information and data on testing and certification of storage tanks for compressed hydrogen and compressed natural gas [7]. It was concluded that there is a need of having sound scientific/technical data available in order to establish a well justified scientific basis for globally harmonized test requirements and procedures for components certification. A round-robin testing program among international testing facilities was strongly recommended at Hydrogen Fuel and Pressure Vessel Forum 2010.

There is a need for collaborative pre-normative R&D and testing which must be peer-reviewed and results made publicly available. There must be statistically reliable test results for essential components comprising the compressed hydrogen storage system of hydrogen fuelled vehicles, which in the case of on-board storage tanks may be difficult as the tests proposed in RCS are lengthy and obtaining sufficient number of tanks will be expensive. Furthermore, results from different test facilities must be independent and comparable [8].

Of particular concern for the JRC is the harmonization of hydrogen gas cycle tests and permeation measurements. Since 2011, commercial hydrogen tanks have been subjected in the JRC-IET's GasTeF facility to hydrogen filling–emptying cycles to investigate their long-term mechanical and thermal behaviour and their safety performance. JRC experimental activities are complemented by computational fluid dynamics (CFD) modelling of the hydrogen filling process by means of a numerical model previously developed and validated at the JRC-IET [9,10].

GasTeF description

Purpose

The high pressure gas tank testing facility GasTeF is designed to perform two of the standardised tests required for the approval of a high pressure storage tank of a hydrogen vehicle:

- Gas cycle test: it consists of tank filling and emptying cycles, in which the tanks are filled up to their nominal working pressure and then emptied, for a number of cycles required to simulate their lifetime. Typical filling times range from 3 to 5 min, while the emptying period can extend up to one hour. Helium, hydrogen or natural gas can be used.
- Gas permeation: it consists of the measurement of gas leaks or permeation from the tank kept at its nominal working pressure for a long period of time (typically 100–500 h). As for the gas cycle test, helium, hydrogen or natural gas can be used, but hydrogen is the one of major interest.

These two tests simulate the service conditions that a tank of a typical hydrogen vehicle experiences during its operative life: a quick filling at the hydrogen refuelling station, an idle or parking period and a slow emptying due to hydrogen consumption during driving.

Description

GasTeF consists of a half-buried concrete bunker with an attached gas storage area in open air. A more detailed description of the GasTeF system and its equipment can be found in Ref. [11]. The facility consists of the following major components:

- a gas compressor with its auxiliary equipment such as hydraulic cooler and control unit,
- a hydrogen pre-cooler, to control hydrogen temperature before entering the test tank,
- a vessel where the tanks to be tested are placed together with the required experimental diagnostic and monitoring equipment,
- a control system made of hardware and software components, for safety operation and data acquisition.

Functioning

Basically, the operations required to perform hydrogen cycle and permeation tests can be reduced to only three: the pressurisation (filling) of the tank, a pressure holding phase and finally the decompression (emptying) of the tank. By means of the three basic operations and by varying starting and final pressures, environmental and gas temperatures and gas mass flow rates it is possible to tailor the experimental conditions to the objectives of the tests. For example, the hydrogen cycle test requires a high filling rate as the fill time shall be less than or equal to 5 min, while the emptying duration is not a critical parameter, as the requirement specifies that the total cycle time shall be less than or equal to one hour [3]. In any case, emptying speed shall be slow enough to avoid tank temperatures below −40 °C and to prevent any tank damage. A quick emptying is on the contrary required to simulate rapid decompression as it can occur during car maintenance. Finally, for the permeation the speed for the filling is not relevant, but the holding phase is extended for many hundreds of hours according to the requirement of the standard.

In all cases, filling is realised in two successive phases, namely a pressure equilibration phase followed by a gas compression phase. At the start of the filling, when the tank is empty, the external hydrogen storage is directly connected to the tank and the gas flow is driven by the pressure difference between storage and tank. When this pressure difference is reduced below a predetermined value, the compressor starts to pump further the hydrogen up to the target test pressure.

The same procedure is executed for the decompression (emptying) of the tank, with the difference that the first pressure equilibration occurs between the full tank and the

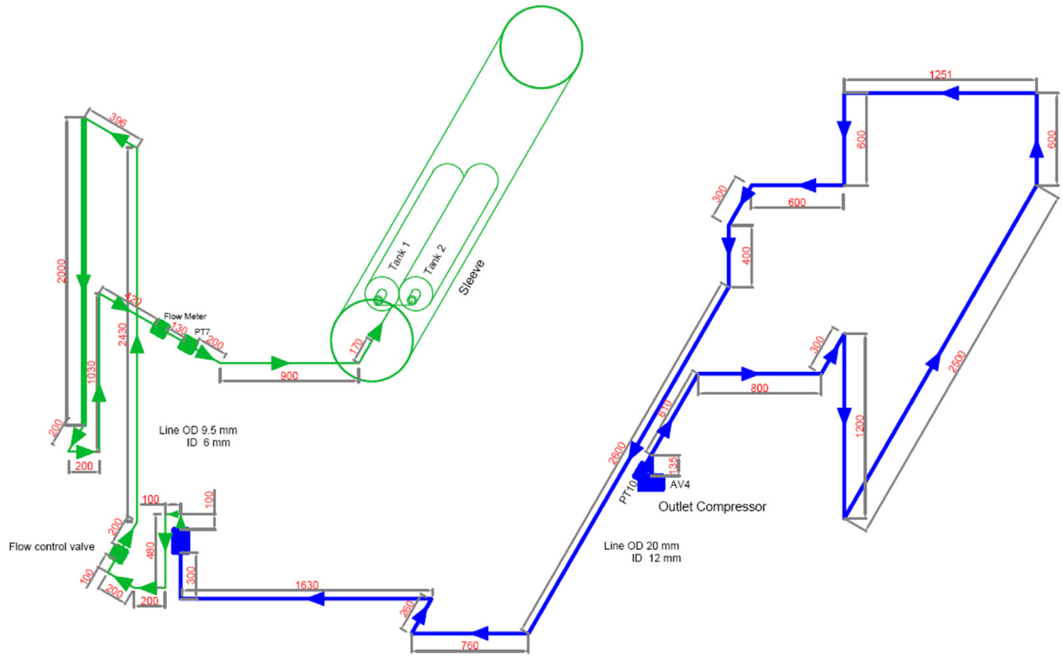

Fig. 1 – GasTeF hydrogen flow path. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

empty hydrogen storage, in this stage the emptying speed is controlled by increasing or reducing a valve aperture.

When gas conditioning is required to simulate hydrogen fuelling activities [12] or as stated in the standards SAE J2579 [1] and ISO 15869 [3] for hydrogen container tests, a heat exchanger is used for pre-cooling the hydrogen prior to its introduction in the tank. The hydrogen-cooler consists of high pressure stainless steel pipes formed in a coil which is submerged in liquid nitrogen. During the tank filling hydrogen passes through the cooler in counter-flow to the nitrogen vapour and during the emptying the cooler is by-passed. The flowing hydrogen is cooled to temperatures down to −40 °C prior to fill the tank under test so that the filling is done in a short time (less than five minutes) without exceeding the 85 °C in the tank as established in the standards.

Hydrogen path

For modelling purposes is important to know the path that the hydrogen gas has followed before entering into the test tank. Fig. 1 depicts the gas flow within GasTeF, outlining how the hydrogen is passing from the exit of the compressor, passing a flow control valve and the hydrogen-cooler to enter the test tank. The compressor and the test installation are connected with high pressure stainless steel piping. The gas line at the first part of the path (blue line in Fig. 1) from the compressor exit has an internal diameter of 12 mm whilst the second part (green line in Fig. 1) until the inlet of the tank is a pipe of 5 mm internal diameter. The pressure value at the final part of the path is given by a pressure transducer (PT-7 in Fig. 1) placed in the gas line at 1270 mm from the tank inlet.

Tests performed with a pressure transducer placed immediately before the tank inlet has shown that the pressure measured does not differ from that of the PT-7 point. The actual pressure in the tank is measured by means of a pressure transducer placed at the tank rear side. Also this pressure does not significantly differ from the pressure at the tank inlet as can be seen in Fig. 2. This figure shows the pressure evolution during the filling part of a cycle test and it can be noted that at the beginning of the filling the tank is empty while there is some hydrogen remaining in the pipeline from the previous cycle. This difference disappears as soon as the pressures in the tank and line are equalised. In Fig. 2 can also be observed how the oscillation in pressure due to the compressor work becomes more noticeable at the end of the filling.

The temperature of the gas is measured at different points along the gas path, namely at compressor exit, at the cooler exit in the same location of PT-7 and 250 mm before the tank inlet.

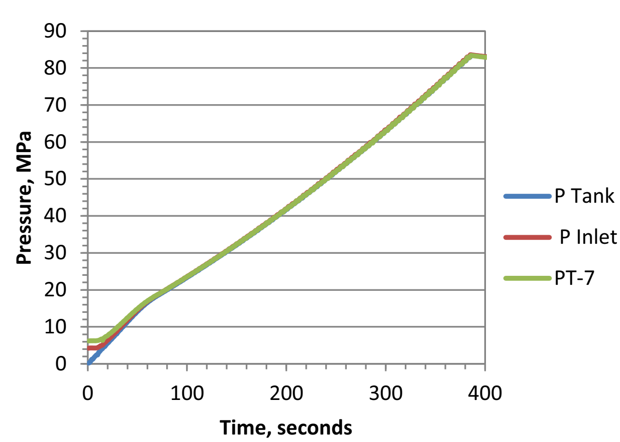

Fig. 2 – Comparison of pressures measured at different locations.

Database experimental description

Tested tanks

To date a number of 70 MPa Nominal Working Pressure hydrogen tanks of three different types have been tested in GasTeF: type 3 of 40 L volume, type 4 of 29 L and 19 L type 4. In Table 1 the characteristics of the tanks are given.

The used inlet ports have an orifice of 3 mm diameter.

Measuring instrumentation

Tanks are instrumented with eight thermocouples and with resistance temperature detectors (RTD) arranged as depicted in Fig. 3. The temperature detectors (four in most of the cases) are fixed at the outer surface and are named according to their location (T_{Top}, T_{Bottom}, T_{Front}, and T_{Line}, which is placed at the outer of the inlet line). The thermocouples are placed inside the tank, thermocouples 7 and 8 are inserted through the gas inlet opening whilst the other internal thermocouples are mounted on a special tree shape array designed at JRC-IET, which is introduced at the rear of the tank (opposite to the gas inlet) and can be axially displaced so that the distance of the thermocouples to the gas inlet can be adjusted. The thermocouple number 5 acts as reference for all temperature measurements and remains therefore in a fixed position even if the array's location is adjusted. The external RTD T_{Top} is placed on the tank surface in correspondence to the reference thermocouple 5.

In some of the experiments a 1 mm thermocouple has also been inserted at the tank inlet.

The thermocouples have a diameter of 1 mm and are of type K, capable of measuring in a range of −200 to 1250 °C with an uncertainty of 2.2 °C. Their response time in air moving at 2 m/s is 3 s to reach 50% of the instantaneous temperature change and 10 s to reach 90%. The RTD has a nominal resistance of 100 Ohms at 0 °C and are capable of measuring temperatures in a range of −100 °C to 550 °C with a maximum deviation of 1.25 °C.

The gas pressures at the inlet/outlet and inside the tank are measured using pressure transducers. To be able to measure

Table 1 – Tested tanks at GasTeF.

	Type 4 19 L	Type 4 29 L	Type 3 40 L
Materials			
Liner	HDPE	HDPE	AA
End bosses	AA	SS	AA
Composite shell	CFRE	G&CFRE	CFRE
Vessel mass (kg)	18.3	32.9	41.5
Storage volume (L) (at 700 bar)	19	28.9	40
H_2 capacity (kg) (with fill density of 40.22 kg/m^3)	0.76	1.16	1.60
Unpressurized dimensions (mm)			
External length	904	827	920
External diameter	228	279	329
Internal diameter	180	230	290

HDPE: High density polyethylene, CFRE: Carbon fibre-reinforced epoxy, G&CFRE: Glass and carbon fibre-reinforced epoxy, AA: Aluminium alloy, SS: Stainless steel.

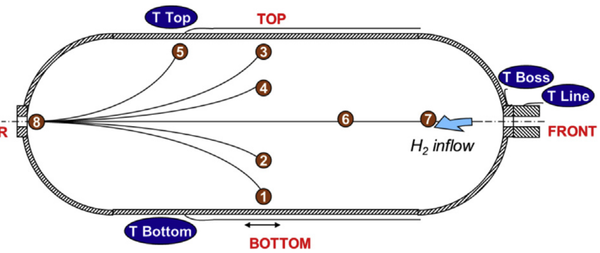

Fig. 3 – Arrangement of the temperature measurement instrumentation in the tanks.

the whole pressure range from 1 to 100 MPa with the required accuracy, two different transducers are used, one calibrated for the low end of the pressure range, the other for the high end. For the high range pressure transducer (0–100 MPa) the error is 5% (full scale) for pressures below 10 MPa and 0.64% at 70 MPa whereas for the transducer calibrated for low pressures, 0–2.5 MPa, the error is 0.4%. The time interval for pressure and temperature data logging is 0.6 s.

Test conditions

A considerable number of fast filling and hydrogen cycle tests have already been carried out in GasTeF. Several starting and end pressures have been considered and different Average Pressure Ramp Rates (APRR) have been imposed. For the most typical filling conditions (e.g. 2–72 MPa) more than one APRR is applied. Some of the APRR are unrealistic from the point of view of hydrogen vehicle refuelling however they are interesting when studying the evolution of temperatures during tank filling.

Most of the filling are done when the tank is in steady-state condition at room temperature but some of the fillings are part of a cycling sequence and are starting after the decompression phase; hence the temperature of the gas remaining in the tank is low and un-homogeneous, even reaching negative values in some points. Common to all tests is that they have been performed with the tank environment maintained at room temperature.

In total the database has 165 entries for tests conducted on type 3 and type 4 tanks. Fig. 4 displays the amount of tests

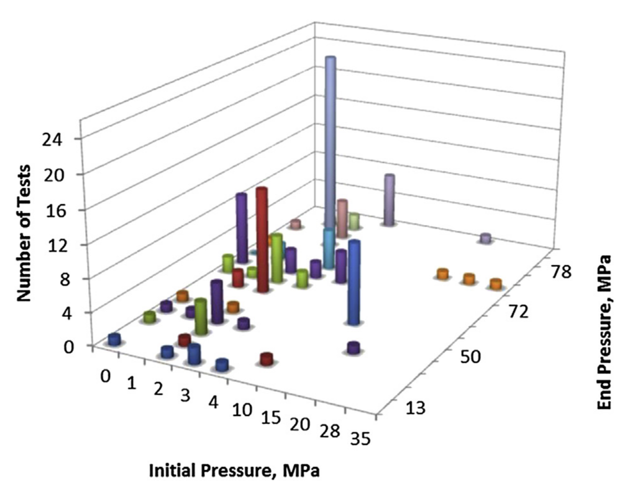

Fig. 4 – Matrix of 133 tests made on type 4 tanks.

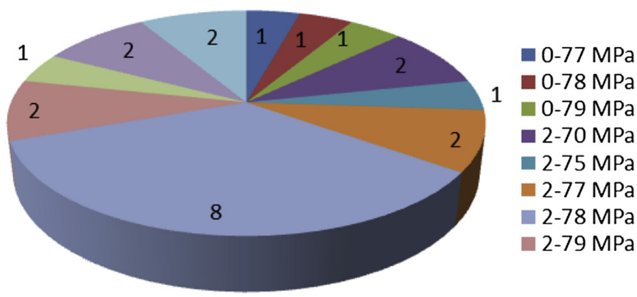

Fig. 5 – Tests made on type 3, 70 MPa tank; H_2 at ambient temperature.

done on type 4 tanks for each filling condition. Fig. 5 summarises the 23 tests conducted on the type 3 tank with hydrogen at ambient temperature, also in this case the most of the tests are done for the filling condition 2–78 MPa.

Database assessment: example of results

Cycling tests

Fig. 6 gives an example of a typical cycle sequence performed in GasTeF. Each hydrogen cycle shown in Fig. 6 consists on a filling of the tank from 3 to 84 MPa, a holding at high pressure during 16 min and a slow tank depressurisation. For three of these cycles the evolution of the pressure and of the gas temperature inside the tank is depicted in Fig. 6. After filling, all temperatures but these measured at the gas inlet (TC7) and at the rear end (TC8) which are influenced by the material of the boss, are equalized. After emptying, however, stratification in gas temperature is significant and a difference of 27 °C from bottom to top of the tank is observed.

In Fig. 6 it can be also noted that the temperature values repeat along the cycles. In fact, after the first 2–3 cycles both the temperature in gas lines and in the tank environment stabilize and all the cycles exhibit the same profile for pressure and temperature evolution. Table 2 shows the statistics for a sequence of 350 cycles; cycles replicate with little standard deviation.

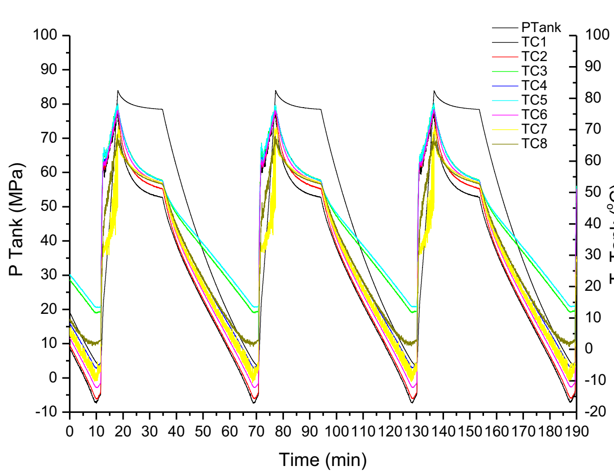

Fig. 6 – Example of filling–holding–emptying cycle.

Table 2 – Statistics sequence of 350 cycles performed with a type 4 19 L tank.

	Mean	Standard deviation
Filling time, (s)	310.4	3.3
Filling initial *P* (MPa)	3.28	0.10
Filling final *P* (MPa)	84.4	0.82
Filling initial *T* (°C)	16.9	0.21
Filling final *T* (°C)	83.1	0.63
PT7 (MPa)	83.7	1.22
Boss initial *T* filling (°C)	11.3	0.09
Boss final *T* filling (°C)	52.6	0.09
Emptying time (min)	33.6	0.09
Emptying initial *P* (MPa)	76.91	0.42
Emptying final *P* (MPa)	2.98	0.08
Emptying initial *T* (°C)	54.5	0.15
Emptying final *T* (°C)	11.4	0.09

Table 3 – Statistics for filling tests 2–76.9 MPa, type 4 29 L tank.

	Mean	Standard deviation
Filling time, (s)	253	1.4
Initial P, (MPa)	1.99	0.36
Final P, MPa	76.89	0.91
Tank averaged initial T, (°C)	11.2	3.7
Tank averaged final T, (°C)	86.9	2.9
Increase in temperature, (°C)	75.6	0.9

Replicability

In order to assess the repeatability of the results, 12 tests with the same filling conditions (2–76.9 MPa at 17.8 MPa/min APRR, without hydrogen pre-cooling) using a 29 L type 4 tank have been separately performed. Table 3 shows the statistical evaluation of these tests. As it can be noted, even if the tank initial temperature is slightly different for the various tests the achieved filling duration and the temperature increases are well reproduced in each test.

Fast filling with pre-cooled hydrogen

Fast filling with cooled hydrogen has been conducted in GasTeF with the aim of proving the pre-cooler capability, for this reason only 9 filling tests of a type 4 29 L tank with cool hydrogen at −42 to −30 °C are currently available in the database, see Table 4.

The SAE J2601 standard establishes the protocol guidelines (algorithm) for fuelling gaseous hydrogen at 35 MPa and 70 MPa into on-road passenger vehicles [12]. When no data

Table 4 – Test conditions type 4 tank 29 L with gas pre-cooling.

Filling condition	APRR (MPa/min)	Gas temperature (°C)	Initial tank temperature (°C)
2–70 MPa	15.5 & 15.8	−30	−5.2 & −13.5
2–77 MPa	17.2	−6.3	−1.7
2–78 MPa	16.5	−42.3	12.7
2–78 MPa	22.2	−30 & −31	15 & 0.44
2–78 MPa	23.5	−4.7	−8.8

Table 5 – Filling with pre-cooled hydrogen at −30 °C test results and validation with SAE J2601.

Pre-cooling temp. (°C)	Tank initial temp. (°C)	End pressure (MPa)	APRR JRC tests (MPa/min)	APRR in J2601 table F-2 (MPa/min)	SoC[b] (%)
−28.8	−5.2	70.2	15.6	16.06[a]	94.6
−29.6	−6.3	70.4	15.8	16.39[a]	93.8
−30	−13.5	70.3	15.5	17.5	95.2
−29	−8.4	70.5	15.5	17.02[a]	95.3
−31	0.44	78.1	22.2	14.5	99.8
−30.2	15	77.9	22.3	10.9	97.8

[a] Extrapolated.
[b] Calculated using the equation in the SAE J2601. Note that the tank initial pressure is 2 MPa for the considered experiments.

communication between the vehicle tank and the refuelling station is available the SAE J2601 defines a "tables-based" approach. This approach uses the ambient temperature measured at the station, the initial measured pressure in the tank and the capacity of tank to "look-up" the average pressure ramp rate and target fill pressure.

Notwithstanding the differences between GasTeF and a hydrogen refuelling station regarding the way of filling the hydrogen tank, the results of the fast filling tests with pre-cooling have been checked with the SAE J2601 tables.

The test conducted with hydrogen at −42 °C, see Table 4, started at 2 MPa but the filling was continued until 78 MPa with an APRR of 16.5 MPa/min. Looking at SAE J2601 Table 8-1 for 20 °C ambient temperature the pressure target for the filling test should have been 73.2 MPa with an APRR of 28 MPa/min; in fact even if the filling is carried out at smaller APRR than 28 MPa/min the state of charge (SoC) of the tank results 101.6%.

The following check is made looking at the SAE J2601's table F-2 (hydrogen dispensed at −20 °C) since in GasTeF experiments the initial tank (inner gas) temperature is known. The results are summarised in Table 5. Regardless of GasTeF's filling tests being performed with hydrogen pre-cooled at −30 °C the applied pressure rate and the achieved SoC for the 70 MPa fillings are in good agreement with the APRR determined by the SAE J2601. For the fillings to 78 MPa the APRR of the test is substantially higher than those of the J2601; however the tank has not been over-charged because the hydrogen temperature is lower than the −20 °C of the table F-2. Looking at the Table F-1, for hydrogen pre-cooled at −40 °C, the corresponding APRR is 28.2 MPa/min, thus in our tests the higher gas temperature and the greater end pressure are compensated by a slower filling.

Summary

The high pressure gas tank testing facility GasTeF is designed to carry out the hydrogen cycle test and the permeation test according to the procedures prescribed by the European Regulation on type-approval of hydrogen vehicles and by other international standards such as SAE. GasTeF results are used to assist technology developments, but also to validate and improve safety and performance requirements for hydrogen tanks for transport applications.

A considerable number of fast filling and hydrogen cycle tests have been conducted in GasTeF. In total the database has 165 entries for tests conducted on type 3 and type 4 commercial tanks. The database contains the results of temperature measurement for many filling and emptying conditions representative of the operation of hydrogen storage tanks.

The GasTeF data will be made publicly available as reference for safety studies and CFD validation. Furthermore JRC-IET is willing to contribute with such test data to inter-laboratory comparisons among other organisations involved in the same type of tests.

Acknowledgements

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